

Evidence for a new Σ^* resonance with $J^P = 1/2^-$ in the old data of $K^-p \rightarrow \Lambda\pi^+\pi^-$ reaction

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Abstract

Distinctive patterns are predicted by quenched quark models and unquenched quark models for the lowest SU(3) baryon nonet with spin parity $J^P = 1/2^-$. While the quenched quark models predict the lowest $1/2^-$ Σ^* resonance to be above 1600 MeV, the unquenched quark models predict it to be around $\Sigma^*(1385)$ energy. Here we re-examine some old data of the $K^-p \rightarrow \Lambda\pi^+\pi^-$ reaction and find that besides the well established $\Sigma^*(1385)$ with $J^P = 3/2^+$, there is indeed some evidence for the possible existence of a new Σ^* resonance with $J^P = 1/2^-$ around the same mass but with broader decay width. Higher statistic data on relevant reactions are needed to clarify the situation.

In the classical constituent quark models, the effective degrees of freedom for a baryon are limited to three constituent quarks. In these quenched quark models with a central monotonic confining interaction, the lowest excitation of baryons is the orbital angular momentum $L = 1$ excitation of a quark, resulting to spin-parity $1/2^-$. Its typical excitation energy is about 450 MeV [1]. However, the experimentally observed lowest $1/2^-$ baryons are $N^*(1535)$, $\Lambda^*(1405)$ and $\Sigma^*(1620)$ [2] with excitation energies of 596 MeV, 290 MeV and 431 MeV, respectively. In these quenched quark models, it is very difficult to understand why the $\Lambda^*(1405)$ with (uds) -quarks is lighter than the $N^*(1535)$ with (uud) -quarks. To solve the mass order reverse problem, it seems necessary to go beyond the simple quenched quark models. In fact the spatial excitation energy of a quark in a baryon is already comparable to pull a $q\bar{q}$ pair from the gluon field. Even for the proton, the well established \bar{d}/\bar{u} asymmetry with the number of \bar{d} more than \bar{u} by an amount $\bar{d} - \bar{u} \approx 0.12$ [3] demands its 5-quark components to be at least 12%. The 5-quark components can be either in the form of meson cloud, such as $n(udd)\pi^+(u\bar{d})$, or in other forms of quark correlation, such as penta-quark configuration $[ud][ud]\bar{d}$ with $[ud]$ -diquark correlation. In either meson cloud model or penta-quark model, the mass order reverse problem of $N^*(1535)$ and $\Lambda^*(1405)$ can be easily explained. In the meson cloud models [4, 5], the $N^*(1535)$ is explained as a $K\Lambda$ - $K\Sigma$ quasi-bound state while $\Lambda^*(1405)$ is a dynamically generated state of coupled KN - $\Sigma\pi$ channels. In the penta-quark models [6, 7, 8], the $N^*(1535)$ is mainly a $[ud][us]\bar{s}$ state while $\Lambda^*(1405)$ is mainly a $[ud][sq]\bar{q}$ state with $q\bar{q} = (u\bar{u} + d\bar{d})/\sqrt{2}$.

These unquenched models give interesting predictions for the isovector partner of the $\Lambda^*(1405)$ and $N^*(1535)$. While the penta-quark models [6, 7] predict a $\Sigma^*(1/2^-)$ resonance with a mass around or less than its corresponding Λ^* partner, the meson cloud model [5] predicts it to be non-resonant broad structure. The predictions of these unquenched models and the classical quenched quark models are distinctive and need to be checked by experiments.

Possible existence of such new $\Sigma^*(1/2^-)$ structure in J/ψ decays was pointed out earlier [9] and is going to be investigated by forthcoming BES3 experiment [10], here we re-examine the old data of $K^-p \rightarrow \Lambda\pi^+\pi^-$ reaction to see whether there is evidence for its existence or not.

The $K^-p \rightarrow \Lambda\pi^+\pi^-$ reaction was studied extensively around 30 years ago for extracting properties of the $\Sigma^*(1385)$ resonance, with K^- beam momentum ranging from 0.95 GeV to 8.25 GeV [11, 12, 13, 14, 15, 16, 17]. In the invariant mass spectrum of $\Lambda\pi$ of this reaction

there is a strong peak with mass around 1385 MeV and width around 40 MeV. The mass fits in the pattern of SU(3) baryon decuplet of $J^P = 3/2^+$ predicted by the classical quark model perfectly. The angular distribution analyses also conclude that the spin of this resonance is $3/2$ [13, 14, 18]. However we found that all these analyses are in fact assuming that there is only one resonance under the peak. Nobody has considered that there are probably two resonances there. This may be because there are no other predicted Σ^* resonances around this mass region in the classical quark models. Since now a new Σ^* with the $J^P = 1/2^-$ around this mass region is predicted by various unquenched models, the old $K^-p \rightarrow \Lambda\pi^+\pi^-$ reaction should be re-scrutinized carefully.

We examined previous experimental analyses [11, 12, 13, 14, 15, 16, 17] on the $K^-p \rightarrow \Lambda\pi^+\pi^-$ reaction. Among them, we find that the invariant mass spectra of $\Lambda\pi^-$ with beam momentum $P_{K^-} = 1.0 \sim 1.8 \text{ GeV}$ [14, 15, 16, 17] are different from others. The peak around $\Sigma^*(1385)$ in these mass spectra cannot be fit as perfect as other sets of data with a single Breit-Wigner resonance. Since Ref.[14] presents the largest data sample and the most transparent angular distribution analysis of this reaction, we re-fit the $\Lambda\pi^-$ mass spectrum and angular distribution of Ref.[14] by taking into account the possibility of two Σ^* resonances in this mass region.

The data in Ref.[14] for the $K^-p \rightarrow \Lambda\pi^+\pi^-$ reaction were taken for beam momentum ranging from $1 \sim 1.75 \text{ GeV}$. To re-fit the invariant mass spectrum of $\Lambda\pi^-$, we assume the following formula:

$$\frac{dN}{dm_{\Lambda\pi^-}} \propto p_1 \times p_2 \times \sum_{i=1}^3 \frac{|a_i|}{(m_{\Lambda\pi^-}^2 - m_i^2)^2 + m_i^2 \times \Gamma_i^2} \quad (1)$$

where two relative momenta p_1 and p_2 come from the phase space factor with

$$p_1 = \sqrt{\frac{(s - (m_{\Lambda\pi^-} - m_{\pi^+})^2) \times (s - (m_{\Lambda\pi^-} + m_{\pi^+})^2)}{4s}}, \quad (2)$$

$$p_2 = \sqrt{\frac{(m_{\Lambda\pi^-}^2 - (m_{\Lambda} - m_{\pi^-})^2) \times (m_{\Lambda\pi^-}^2 - (m_{\Lambda} + m_{\pi^-})^2)}{4m_{\Lambda\pi^-}^2}}. \quad (3)$$

Here we use one Breit-Wigner function describing the reflection background from Σ^{*+} band in the $\Lambda\pi^+\pi^-$ Dalitz plot. And $m_{\Lambda\pi^-}$ represents the invariant mass of $\Lambda\pi^-$. The masses for pions and Λ are taken from PDG [2] as $m_{\pi^+} = m_{\pi^-} = 0.139570 \text{ GeV}$ and $m_{\Lambda} = 1.115683 \text{ GeV}$. s is the invariant mass squared of K^-p . Here we take the central value $s = 4.0 \text{ GeV}^2$ of the experiment [14].

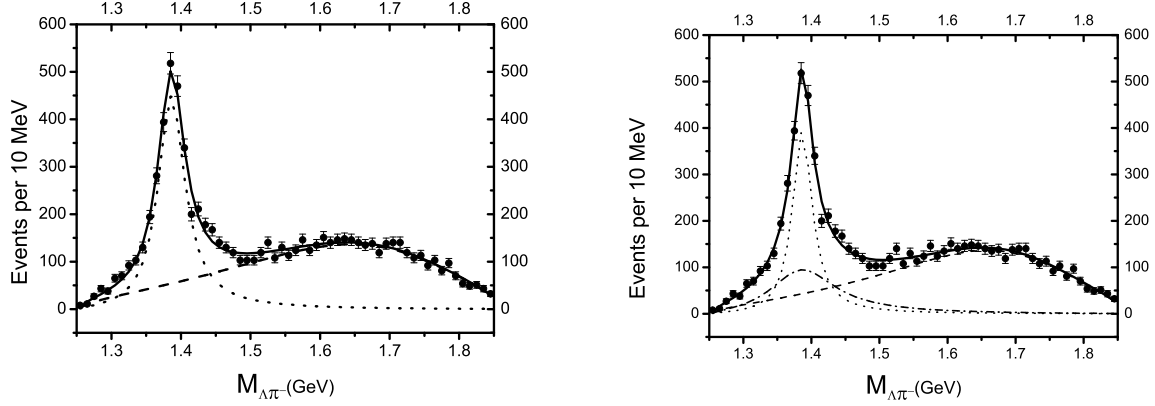


FIG. 1: Fits to the $\Lambda\pi^-$ mass spectrum with a single Σ^* (left) and two Σ^* resonances (right) around 1385 MeV with fitting parameters listed in Table 1. The experiment data are from Ref.[14].

	$M_{\Sigma^*(3/2)}$	$\Gamma_{\Sigma^*(3/2)}$	$M_{\Sigma^*(1/2)}$	$\Gamma_{\Sigma^*(1/2)}$	$\chi^2/ndf(\text{Fig.1})$	$\chi^2/ndf(\text{Fig.2})$
Fit1	1385.3 ± 0.7	46.9 ± 2.5			68.5/54	10.1/9
Fit2	$1386.1^{+1.1}_{-0.9}$	$34.9^{+5.1}_{-4.9}$	$1381.3^{+4.9}_{-8.3}$	$118.6^{+55.2}_{-35.1}$	58.0/51	3.2/9

TABLE I: Fitted parameters with statistical errors and χ^2 over number of degree of freedom (ndf) for the fits with a single (Fit1) and two Σ^* resonances (Fit2) around 1385 MeV.

The results of the fits with a single and two Σ^* resonances around 1385 MeV are shown in Fig. 1 and Table I where fitted parameters with statistical errors are given. The fit with a single Σ^* resonance (Fit1) is already not bad. The fit with two Σ^* resonances (Fit2) improves χ^2 by 10.5 compared with the Fit1 for 60 data points with 3 more fitting parameters. Although this is just a less than 3σ improvement, a point favoring Fit2 is that while the single Σ^* resonance in Fit1 has a width larger than the PDG value [2] of 36 ± 5 MeV for the $\Sigma^*(1385)$ resonance, the narrower Σ^* resonance in Fit2 gives a width compatible with the PDG value for the $\Sigma^*(1385)$ resonance. In the Fit2, there is an additional broader Σ^* resonance with a width about 120 MeV.

The preferred assignment of spin $J = 3/2$ for the $\Sigma^*(1385)$ resonance in Ref. [14] is demonstrated by the distribution of the cosine of the angle between the Λ direction and the K^- direction for the reaction $K^-p \rightarrow \Lambda\pi^+\pi^-$ with $M_{\Lambda\pi^-}$ in the range of 1385 ± 45 MeV

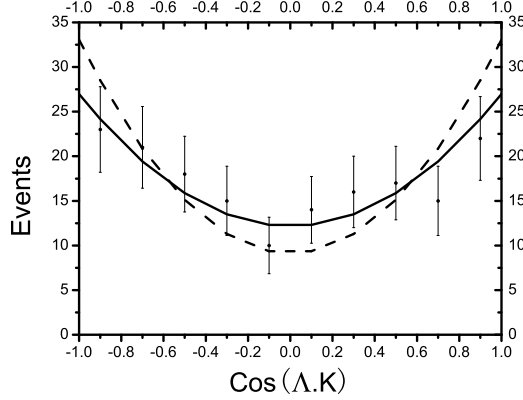


FIG. 2: Predictions for the distribution of the cosine of the angle between the Λ direction and the K^- direction for the reaction $K^-p \rightarrow \Lambda\pi^+\pi^-$ by Fit1 (dashed curve) and Fit2 (solid curve), compared with the data from Ref. [14] .

and $\cos\theta_{K\Sigma^*} > 0.95$. For a Σ^* with $J = 3/2$, the angular distribution is expected to be of the form $(1 + 3\cos^2\theta)/2$ [14, 19]; while for a Σ^* with $J = 1/2$, a flat constant distribution is predicted. The data [14] as shown in Fig.2 clearly favor the case of $J = 3/2$ if only a single Σ^* resonance is assumed. However, here we want to show that the Fit2 with two Σ^* resonances with the narrower one of $J = 3/2$ and the broader one with $J = 1/2$ reproduces the data even better.

For the experimental angular distribution shown in Fig.2, only data for beam momentum of $1 \sim 1.45$ GeV are used because the background problem is considered too severe for momenta above 1.45 GeV [14]. For $M_{\Lambda\pi^-}$ in the range of 1385 ± 45 MeV and beam momentum of $1 \sim 1.45$ GeV, we obtain the ratio of the narrow $\Sigma^*(1385)$ contribution to be 93% and 58% for Fit1 and Fit2, respectively. If assuming the broader Σ^* resonance has spin $J = 1/2$ which gives a flat angular distribution as background term, then the predictions of Fit1 and Fig.2 for the angular distribution are shown by the dashed curve and solid curve with χ^2 of 10.1 and 3.2, respectively, in Fig.2. In the Fit2, the ratio of contributions from the narrow $\Sigma^*(1385)$ and the broader Σ^* is about 1.6.

From above results, we find that the inclusion of an additional $\Sigma^*(1/2^-)$ besides the well-established $\Sigma^*(1385) 3/2^+$ seems improving the fit to the data for both $\Lambda\pi^-$ invariant

mass spectrum and the angular distribution although the large error bars for the angular distribution data make it not very conclusive.

For the reaction $K^-p \rightarrow \Lambda\pi^+\pi^-$, the evidence of the $\Sigma^*(1/2^-)$ seems most visible in the $\Lambda\pi^-$ decay channel for the beam momentum in the range of $1.0 \sim 1.8$ GeV. The evidence is much weaker, if any, in the $\Lambda\pi^+$ channel and at other beam momenta. The possible reason could be due to different production mechanisms for the Σ^{*-} and Σ^{*+} . While u -channel nucleon exchange can only produce Σ^{*-} not Σ^{*+} , the t -channel K^* exchange is just opposite, as shown by Fig.3(a) and Fig.3(b), respectively. The different production mechanisms have different energy-dependence. These points need more theoretical investigation.

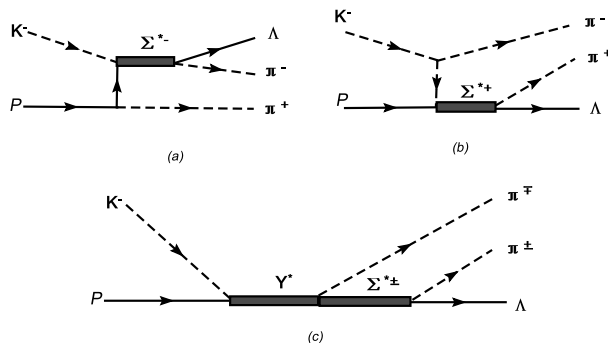


FIG. 3: Feynman diagrams for the $K^-p \rightarrow \Lambda\pi^+\pi^-$ reaction.

Recently, LEPS Collaboration has reported its measurement of beam asymmetry for the $\gamma n \rightarrow K^+\Sigma^{*-}$ reaction [20]. The beam asymmetries are negative, in contrast with theoretical prediction of positive values [21] by assuming dominant $\Sigma^*(1385)$ with $J^P = 3/2^+$. This also indicates that there should be important partial wave component(s) other than $J^P = 3/2^+$ under the $\Sigma^{*-}(1385)$ peak.

In summary, distinctive patterns are predicted by quenched quark models and unquenched quark models for the lowest SU(3) baryon nonet with spin parity $J^P = 1/2^-$. While the quenched quark models predict the lowest $1/2^-$ Σ^* resonance to be above 1600 MeV, the unquenched quark models predict it to be around $\Sigma^*(1385)$ energy. Here we re-examine some old data of the $K^-p \rightarrow \Lambda\pi^+\pi^-$ reaction and find that besides the well established $\Sigma^*(1385)$ with $J^P = 3/2^+$, there is indeed some evidence for the possible existence of a new Σ^* resonance with $J^P = 1/2^-$ around the same mass but with broader decay width. There are also indications for such possibility in the $J/\psi \rightarrow \bar{\Sigma}\Lambda\pi$ and $\gamma n \rightarrow K^+\Sigma^{*-}$ reactions.

At present, the evidence is not strong. Therefore, high statistics studies on the relevant reactions, such as $K^-p \rightarrow \pi\Sigma^*$, $\gamma N \rightarrow K\Sigma^*$, $J/\psi \rightarrow \bar{\Sigma}\Sigma^*$ with $\Sigma^* \rightarrow \Lambda\pi$, are urged to be performed by forthcoming experiments at JPARC, CEBAF, BEPCII, etc., to clarify the situation.

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